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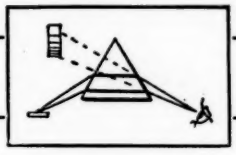

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*Journal of the*
# OPTICAL SOCIETY *of* AMERICA

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## Graphical Exposition of the Michelson-Morley Experiment

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(Received January 22, 1937)

THE progress of a light wave or pulse in the Michelson-Morley experiment is most simply comprehended by imagining the interferometer to consist of three intersecting mirrors, two at right angles (end mirrors) and the third (inclined mirror) at 45° to the first two, and considering the manner in which the incident light pulse is broken up into reflected pulses pivoting about the point of intersection of the mirrors.[1] For this purpose we utilize the well-known formula for reflection of light at a moving oblique mirror[2] derived from the Huygens' construction, from which it follows that the reflection deviates from the direction for a stationary mirror by the "aberration angle" $\sin^{-1}(v/c)$, where $v$ is the velocity of the apparatus, and $c$ the velocity of light, plus or minus higher order terms in $v/c$, of which the second-order term, called by Lodge "the error of reflection," is $\frac{1}{2}v^2/c^2$. As a consequence two pulses leave the point of intersection of the mirrors, inclined to the angle of incidence of the original pulse by 90° plus or minus $v/c$ (if the angle is small), and inclined to each other by the small angle $v^2/c^2$. If the point of observation is at the end of the inclined mirror away from the point of intersection, and the length of the interferometer is $L$, the path difference between the sections of the emergent pulses observed is $L(v^2/c^2)$.

In order to exhibit the phenomena the chart (Fig. 1) has been drawn with the arbitrarily high value 0.4 chosen for $v/c$. In the figure each column presents successive positions in left to right motion of one orientation of the interferometer with respect to the direction of motion. $S_0$ is the position of the light source when a light pulse is emitted, $S$ its position when the light pulse, after passage through a lens $N$, enters the apparatus as a plane pulse or wave, represented by a long dashed line. $D$, $R$ and $M$ are the two end mirrors and the diagonal mirror of the interferometer. The short-dashed and the dotted lines represent the two elements into which the pulse is split after undergoing reflection. $W_R$ and $W_D$ are the emergent pulse fronts coming respectively from end mirrors $R$ and $D$. The point of observation, occupied by some detector such as a radiometer, is at O. The development of the emergent light pulses can be readily followed in the successive positions taken by the interferometer moving from left to right in each column. Note that for the 90° and 270° orientations the light pulse is *incident at the aberration angle* (due to the motion of the apparatus during the time taken by the light to travel from the source), and leaves with or against the direction of motion; for the 0° and 180° orientations the light enters

[1] Kennedy "Simplified Theory of the Michelson-Morley Experiment," Phys. Rev. **47**, 965 (1935).
[2] Vide Silberstein, *Theory of Relativity*, p. 90.



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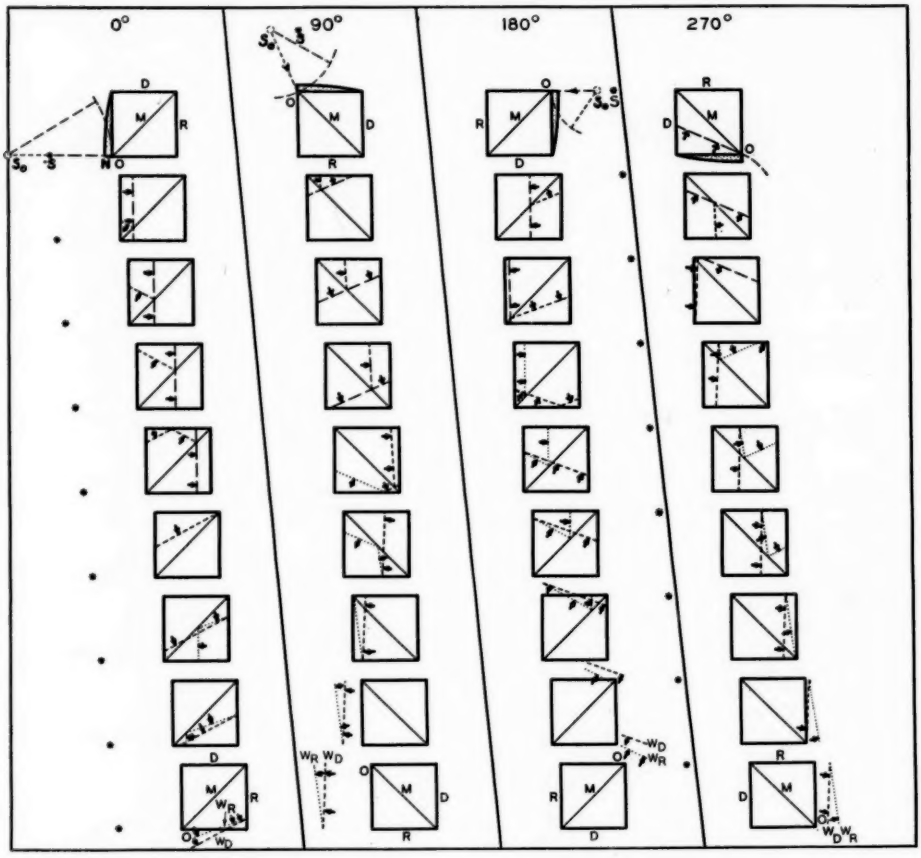


FIG. 1.

with or against the direction of motion, and *leaves at the aberration angle;* in each case leaving with the small inclination $v^2/c^2$ between the two pulses.

Looking at the final difference of path as the result of the error of reflection, due to motion, the Fitzgerald-Lorentz contraction may be considered as a means of introducing a *tilt* of the inclined mirror just sufficient to correct this error and bring the two emergent pulses into coincidence. The contraction of dimensions necessary to produce this tilt consists of *any* relative contraction in the directions parallel and perpendicular to the direction of motion having the relation $(1-v^2/c^2)^{\frac{1}{2}} : 1$. A similar chart to Fig. 1, introducing this tilt, would show the schematic interferometers not as squares, but as rectangles narrow in the horizontal direction. The light pulses, while entering or leaving the apparatus at the aberration angle, as already discussed, would show the two pulses produced by division at the diagonal mirror, leaving in coincidence.[3]

The Fitzgerald-Lorentz contraction is usually understood to be a contraction only in the direction of motion, of value $(1-v^2/c^2)^{\frac{1}{2}}$. By the elementary theory of the experiment the length of path traversed by the pulse traveling parallel to the direction of motion is $2L/(1-v^2/c^2)$, that of the pulse traveling at right angles is

$$2L/(1-v^2/c^2)^{\frac{1}{2}}.$$

As a result of the contraction in the one direction,

[3] See appendix for proof that the Fitzgerald-Lorentz contraction brings the pulse fronts into *exact* coincidence.

the two paths both assume the value

$$2L/(1-v^2/c^2)^{\frac{1}{2}}.$$

They are *equal* for all orientations of the apparatus *at a given velocity*, but both vary together for different velocities.

Another contraction, which produces the same tilt, is a contraction of value $1-v^2/c^2$ in the direction of motion, and of value $(1-v^2/c^2)^{\frac{1}{2}}$ in the direction perpendicular to the motion. This results in both path lengths being *always 2L, irrespective of orientation or velocity.*

The original form of the Michelson-Morley experiment, in which both interferometer arms are of equal length, is equally well satisfied by either kind of contraction. In the experiment of Kennedy and Thorndyke,[4] where the interferometer arms are of unequal length, this is not the case. The null result of that experiment, as the apparatus presumably assumed different velocities with the motion of the earth over extended periods, *requires an actual constancy of both path lengths at all velocities.* This is satisfied by the second form of contraction above considered, as is shown by Table I which gives path lengths and differences for pulses parallel and perpendicular to the direction of motion, for the 0° orientation, assuming interferometer arms of lengths $L$ and $KL$.

For the unidirectional contraction the path difference $\Delta P$ is a function of the velocity, except for the case of $K=1$. The relations shown in the table are embodied in a graphical presentation of the path lengths for all orientations, in Fig. 2. (The radicals of the table have been expanded to the 2nd order for insertion in the diagram.)

Kennedy and Thorndyke actually performed their experiment as a test of the hypothesis of Larmor and Lorentz that a moving light source is reduced in frequency in the ratio $(1-v^2/c^2)^{\frac{1}{2}}:1$ whereby the product of distance by measured time would remain constant at all velocities, if the contraction were the unidirectional one. The experiment is, however, equally well explained by assuming an unequal contraction of the apparatus in two directions, and no change in time reckoning.

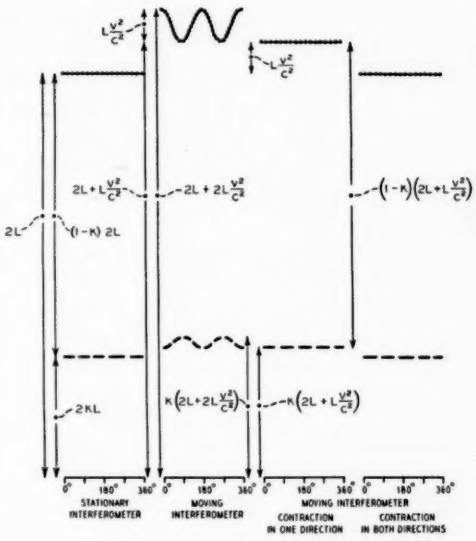


FIG. 2.

The line of analysis may be pursued further to yield the following general formulae:

$[(1-v^2/c^2)^{\frac{1}{2}}]^{n+1}$ for contraction in the direction of motion

$[(1-v^2/c^2)^{\frac{1}{2}}]^{n}$ for contraction at right angles to the direction of motion

$[(1-v^2/c^2)^{\frac{1}{2}}]^{1-n}$ for reduction in clock frequency.

[4] Kennedy and Thorndyke, "Experimental Proof of the Relativity of Time," Phys. Rev. **42**, 400 (1932).

TABLE I.

| | Path Length in Direction of Motion | Path Length Perpendicular to Motion | Difference of Path |
|---|---|---|---|
| (1) No contraction | $P_1=\frac{2L}{(1-v^2/c^2)}$ | $P_2=\frac{2KL}{(1-v^2/c^2)^{\frac{1}{2}}}$ | $\Delta P=L\frac{v^2}{c^2}$ |
| (2) Contraction in one direction | $P_1=\frac{2L}{(1-v^2/c^2)^{\frac{1}{2}}}$ | $P_2=\frac{2KL}{(1-v^2/c^2)^{\frac{1}{2}}}$ | $\Delta P=\frac{2L(1-K)}{(1-v^2/c^2)^{\frac{1}{2}}}$ |
| (3) Contraction in both directions | $P_1=2L$ | $P_2=2KL$ | $\Delta P=2L(1-K)$ |

Using these formulae in the Kennedy-Thorndyke experiment we get for the *measured* time interval between arrival of reflected pulses at the origin

$$\Delta T=\left(\frac{L}{c}\frac{[(1-v^2/c^2)^{\frac{1}{2}}]^{n+1}}{1-v^2/c^2}-\frac{kL[(1-v^2/c^2)^{\frac{1}{2}}]^n}{c(1-v^2/c^2)^{\frac{1}{2}}}\right)\times[(1-v^2/c^2)^{\frac{1}{2}}]^{1-n}$$

$$=(L/c)(1-k).$$

There is thus always a possible clock rate to make the time interval measure constant, whatever contractions, in the ratio $(1-v^2/c^2)^{\frac{1}{2}}:1$ in the two principal directions are assumed. This shows that the experiment of Kennedy and Thorndyke (and any experiment depending on light signals returned to the origin by reflection) is not by itself a test of the Larmor-Lorentz hypothesis; it must be supplemented by independent support for the choice of the exponent $n$ in the above equation.[5]

Attention may be called finally, to the fact that while the contractions of dimensions which have been considered result in equalizing the light *path lengths* in the two arms of the interferometer, the wave fronts still enter or leave the apparatus *at an angle* to the axis, namely the aberration angle. The contraction merely compensates for the deviation of the reflections from the aberration angle. Conditions are not therefore *in all respects* identical in a stationary system and a moving system experiencing a Fitzgerald-Lorentz contraction.

## Appendix

### Proof that the Fitzgerald-Lorentz contraction exactly compensates the error of reflection

In the schematic interferometer (Fig. 3) let the light be incident from left to right, which is also the direction of motion of the apparatus. The stationary dimensions of the apparatus are $L\times L$; in motion at the velocity $v$, the length in the direction of motion is $L(1-v^2/c^2)^{\frac{1}{2}}$.

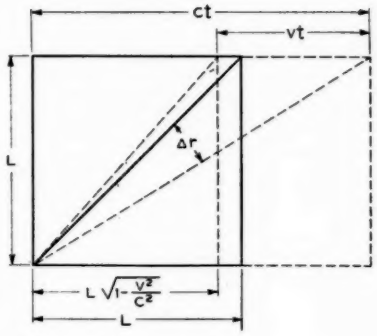


FIG. 3.

Let $t$ be the time taken by the light pulse to travel from its point of first incidence on the diagonal mirror to the point of intersection of the diagonal and plane mirrors, the latter point having moved the distance $vt$. We then have

$$ct=vt+L(1-v^2/c^2)^{\frac{1}{2}}$$

or
$$L^2=c^2t^2(1-v/c)/(1+v/c).$$

Now the angle $\Delta r$, by which the moving diagonal mirror differs from $\pi/4$ is one-half the angle $\theta$, by which the reflected light will deviate in direction from $\pi/2$. We have the trigonometrical relation

$$\frac{\sin\Delta r}{vt-L(1-(1-v^2/c^2)^{\frac{1}{2}})}=\frac{1/\sqrt{2}}{(c^2t^2+L^2)^{\frac{1}{2}}}.$$

Substituting the value of $L$ we get

$$\sin\Delta r=\frac{(1+v/c)^{\frac{1}{2}}-(1-v/c)^{\frac{1}{2}}}{2}=\sin\theta/2,$$

from which
$$\sin^2\theta/2=\frac{1-(1-v^2/c^2)^{\frac{1}{2}}}{2}$$

and
$$\cos^2\theta/2=1-\sin^2\theta/2=\frac{1+(1-v^2/c^2)^{\frac{1}{2}}}{2},$$

$$\sin\theta=\sqrt{4\sin^2(\theta/2)\cos^2(\theta/2)}=v/c;$$

that is, the deviation of the reflected pulse front from its direction for stationary apparatus is exactly at the aberration angle. The proof is obviously the same for any contractions of the apparatus dimensions in the ratio $(1-v^2/c^2)^{\frac{1}{2}}:1$.

[5] Kennedy and Thorndyke recognize, in their introductory paragraphs, that any contractions, having the ratio $(1-v^2/c^2)^{\frac{1}{2}}:1$ are equally valid for explaining the original Michelson-Morley experiment, but restrict their attention to the unidirectional one in interpreting their result as ". . . proof of the relativity of time."

# The Optical Constants of Sodium

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(Received January 28, 1937)

IN a recent paper[1] in this journal the authors reported the results of measurements of the optical constants of potassium in the range λ2536 to λ5780. The present paper reports the results obtained with sodium as the reflecting metal. As the apparatus and method of making observations were described in detail in the paper dealing with potassium, only a brief summary will be given here.

The method is that of Voigt, as used by Minor and others. Monochromatic plane polarized light is incident on the metallic surface, and after reflection passes in succession through a Babinet compensator, a pair of rotary quartz wedges, and an analyzing Nicol. A spot pattern results which, for the ultraviolet, is recorded photographically. The coordinates of the spot centers with relation to a fixed pair of cross hairs are determined and from these the azimuth of restored plane polarization, $\theta$, may be determined directly. For the determination of $\Phi$, the relative phase shift on reflection, a comparison plate is necessary. The comparison plate is obtained by allowing the plane polarized light to pass directly to the Babinet Rotary-Quartz Analyzer system. In order to reduce the effect of certain errors in adjustment, comparison and reflection plates are taken in pairs; one with light polarized at 45° to the plane of incidence, the other with light polarized at 135° to the plane of incidence.

The formula used for the calculation of the optical constants is that developed by Fry[2] (Eq. 55).

$$N+iK_0=\tan I\left[\frac{(\rho+1)^2-4\rho\sin^2 I}{(\rho+1)^2}\right]^{\frac{1}{2}},$$

where $\rho=e^{i\Phi}\tan\theta$.

In the above formula $I$, $\Phi$, and $\theta$ represent the incidence angle, the relative phase shift on reflection, and the azimuth of restored plane polarization, respectively. $N$ and $K_0$ are the index of refraction and the extinction coefficient for normal incidence. It is to be noted that the $N$ and $K_0$ obtained from this formula are to be identified with the $n_0$ and $n_0\kappa_0$, respectively, of the Drude formula, i.e., the constants for normal incidence.

## CHOICE OF METHOD FOR PREPARING SODIUM SURFACES

In the previous work on potassium the reflecting surface was in the form of a sandwich of potassium between two plates, one of glass, the other of strain free optically flat fused quartz. Measurements were made on the quartz-potassium surface at 60° incidence, utilizing a 60° fused quartz prism sealed to the quartz plate with paraffin oil to eliminate front surface reflections. In spite of precautions taken to protect the exposed edges of potassium, leaks developed which eventually destroyed the surface. With sodium mirrors prepared in this way the etching of the quartz which accompanied any deterioration of the sodium was so severe as to require complete regrinding and polishing of both prism and plate. Two sodium mirrors of this type were produced which had sufficient life for measurement. They, however, developed a serious defect due to lack of control of the temperature of the sandwich assembly while the sodium was passing from liquid to solid state. The effect of unequal cooling in this process was a warped quartz plate, giving a decidedly astigmatic image. Inasmuch as an alternative method for sodium was available it was decided not to risk the quartz prism in further trials.

In some preliminary work it had been found possible to produce a free surface of sodium in vacuum of good specular quality on the flattened surface of a bulb. The details of preparation of such a surface will be described in the next paragraph. As any method using a free surface involves the use of quartz windows for the incident and emergent light, the question of

[1] Herbert E. Ives and H. B. Briggs, J. O. S. A. **26**, 238 (1936).
[2] T. C. Fry, J. O. S. A. **16**, 1 (1928).

disturbances introduced by the windows was given careful consideration.

The form of the tube used is shown in Fig. 1. $D$ is a bulb with a flattened side which was surfaced and polished for first quality reflection. The surfaced area was about $1\frac{3}{8}''$ in diameter. $A$ and $B$ are fused quartz windows, $1''$ in diameter, on step seals to Pyrex tubing. $C$ is a Pyrex window used for adjusting the surface perpendicular to the plane containing the collimator and camera axes. $E$ is a side tube leading to the sodium supply. $F$, $G$, $G$ represent the sodium supply tube and the arrangement used for distillation.

The main tube was first pumped and baked out at 500° to 550°C. During this procedure the sodium, which was outside the furnace enclosure, was given a preliminary outgassing by flame and collected in the lower part of the first distilling tube. After cooling, the sodium was distilled by successive stages into the main tube, the walls and windows being flamed freely to cause the vapor to condense on the bulb $D$ and its supporting stem. According to Mr. G. R. Stilwell, who prepared the tubes, the best surfaces resulted when the temperature of $D$ was kept just below the point where the sodium would liquify. As the upper portion of the stem was warmer than the bulb, the formation of molten drops along the stem was a signal to stop flaming. In case the sodium showed signs of running down on the bulb a few drops of liquid air in the bulb stem would keep it in control. When an opaque film had been built up, the sodium supply and pump leads were sealed off and warm oil was poured into $D$. The oil was maintained at a temperature a few degrees below the melting point of sodium for about an hour, and then allowed to cool a few degrees an hour to room temperature. Surfaces prepared in the manner described exhibited very good specular characteristics. The one used in this investigation was prepared over two years ago.

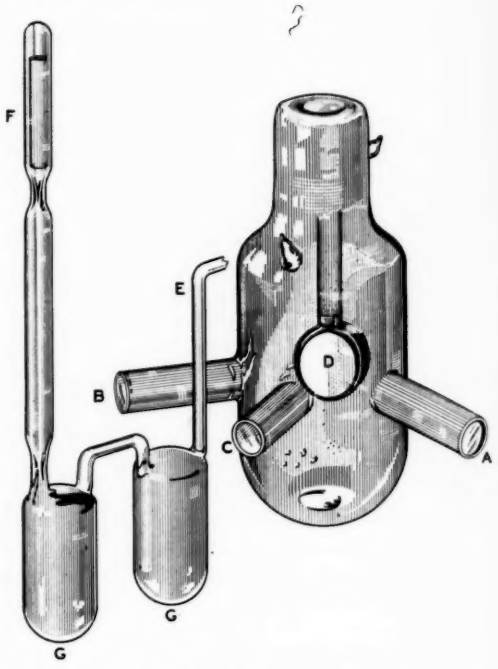


FIG. 1. Tube with sodium mirror.

## WINDOW TESTS

The quartz windows used for the tube were selected from a supply of eight or ten which were on hand. In order to determine if any strains existed in the windows themselves or would develop when the tube was evacuated, the windows were first tested singly and later the tubes supporting the windows were sealed together and the windows tested before and after evacuation. The tests were made with a Babinet compensator of usual design and a pair of Nicol prisms mounted on a spectrometer. For the central portions of the windows no changes in phase or azimuth greater than measurement errors, $\pm 0.5°$ in phase and $\pm 0.1°$ in azimuth, were detected. Near the edges, the windows showed decided strains. In the work which follows, the spots near the edges of the pattern were discarded in the calculations of phase and azimuth.

## ERRORS

A complete discussion of the variations in $N$ and $K_0$ brought about by uncertainties in the experimental determination of $\theta$, $\Phi$ and $I$ would require laborious calculations. For the range of values of $N$ and $K_0$ encountered in this work Table I has been prepared, using selected values of $I$, $\Phi$, and $\theta$ from Table III. Thus the first set

of differences, $\delta N = -0.0132$ and $\delta K_0 = -0.001$ indicate that if the measured value for $\theta$ of 45°12.3′ is replaced by 45°6.3′ the computed $N$ and $K_0$ would be reduced by the amounts shown.

It is evident that small errors in $\theta$, while negligible in their effect on $K_0$, are proportionately large compared with $N$. Errors in $\Phi$ and $I$, on the other hand, affect $K_0$ to a much greater extent than they affect $N$. For the purpose of this table, the dependence of $\theta$ and $\Phi$ on $I$ has been neglected.

The magnitude of the errors assumed in the above table corresponds to what experience and many check measurements have shown to be the upper limit of errors of measurement under good conditions, i.e., a flat specular surface in air. With the introduction of the quartz windows the uncertainty, particularly as regards phase determinations, is increased, possibly by a factor of two.

In connection with the question of instrumental errors it was early noted that consistent results for various angles of incidence could only be obtained when the optical elements were in accurate adjustment. Similarly Emberson[3] found that the variation of $N$ with incidence angle was reduced when certain errors in adjustment were corrected. Assuming for the moment with Emberson the constancy of $N$ with incidence angle as a criterion of the adjustment, the measurements in Table II made on an optically flat plate of Pt-Ir (15 percent Ir) in air afford an indication of the adjustment of our apparatus.

There is a small apparent increase in both $N$ and $K_0$ with decreasing incidence angle, a change which, if real, could be explained only on the assumption of anisotropy in the reflecting surface. Tronstad and Feachem[4] found a similar though larger increase in $N$ for mercury, which they concluded was real.

TABLE I. *Comparative effect of errors.*

| | $\delta\theta = -0.1°$ | | $\delta\Phi = -0.5°$ | | $\delta I = -0.2°$ | |
|---|---|---|---|---|---|---|
| λ | $\delta N$ | $\delta K_0$ | $\delta N$ | $\delta K_0$ | $\delta N$ | $\delta K_0$ |
| 5780 | −0.0132 | −0.001 | −0.0010 | −0.040 | −0.0004 | −0.033 |
| 3650 | −0.0070 | −0.001 | −0.0007 | −0.017 | −0.0005 | −0.017 |
| 2536 | −0.0062 | 0 | +0.0007 | −0.017 | +0.0006 | −0.016 |

[3] Richard M. Emberson, J. O. S. A. **26**, 443 (1936).
[4] L. Tronstad and C. G. P. Feachem, Proc. Roy. Soc. **A145**, 115 (1934).

TABLE II. *Optical constants of Pt-Ir.*

λ = 3650

| $I$ | $\Phi$ | $\theta$ | $N$ | $K_0$ |
|---|---|---|---|---|
| 65° | 115° 15′ | 59° 49′ | 1.60 | 2.30 |
| 60° | 130° 18′ | 57° 55′ | 1.64 | 2.37 |
| 50° | 150° 26′ | 53° 55′ | 1.68 | 2.41 |
| 40° | 162° 46′ | 50° 24′ | 1.67 | 2.48 |
| 30° | 171° 40′ | 47° 56′ | 1.71 | 2.53 |

TABLE III. *Experimental results for sodium.*

| λ | $I$ | $\Phi$ | $\theta$ |
|---|---|---|---|
| 5780 | 56° 21′ | 130° 38′ | 45° 12.3′ |
| 5461 | 57° 15′ | 124° 6′ | 45° 16′ |
| 4358 | 56° 21′ | 115° 30′ | 45° 34′ |
| 4047 | 56° 0′ | 110° 24′ | 45° 39′ |
| 3650 | 56° 21′ | 106° 7′ | 45° 36′ |
| 3126 | 56° 21′ | 92° 59′ | 45° 40′ |
| 2652 | 56° 21′ | 83° 12′ | 45° 28′ |
| 2536 | 56° 21′ | 79° 24′ | 45° 25.5′ |

TABLE IV. *Constants calculated from experimental data.*

| λ | $N$ | $K_0$ | $R(\%)$ | $I'$ | $\theta'$ |
|---|---|---|---|---|---|
| 5780 | 0.027 | 2.59 | 98.6 | 71° 4′ | 45° 16′ |
| 5461 | .029 | 2.32 | 98.2 | 69° 27′ | 45° 18′ |
| 4358 | .048 | 1.80 | 95.6 | 65° 41′ | 45° 36′ |
| 4047 | .048 | 1.56 | 94.5 | 63° 34′ | 45° 40′ |
| 3650 | .042 | 1.44 | 94.7 | 62° 21′ | 45° 36′ |
| 3126 | .040 | 1.02 | 92.6 | 57° 31′ | 45° 40′ |
| 2652 | .028 | .735 | 93.1 | 53° 34′ | 45° 29′ |
| 2536 | .026 | .621 | 92.7 | 51° 52′ | 45° 28′ |

## RESULTS OF MEASUREMENTS ON SODIUM

Table III and Table IV give the results of our measurements on sodium. The measurements at λ5780, 5461 and 4358 were made visually, using the micrometer screw attached to one of the Babinet wedges for the determination of phase shift, the analyzer being utilized for the determination of the azimuth of restored plane polarization. The mean of forty settings each for two mutually perpendicular planes of vibration was used for phase determinations; for the determination of azimuth the number of settings was doubled.

The spot patterns for λ4047, 3650, 3126, 2652 and 2536 were recorded photographically. At λ4047 four plates were measured, two for each of the two planes of vibration used. At λ3650 six plates were measured, at λ3126, 6 plates, at λ2652, two plates, and at λ2536, 4 plates. In

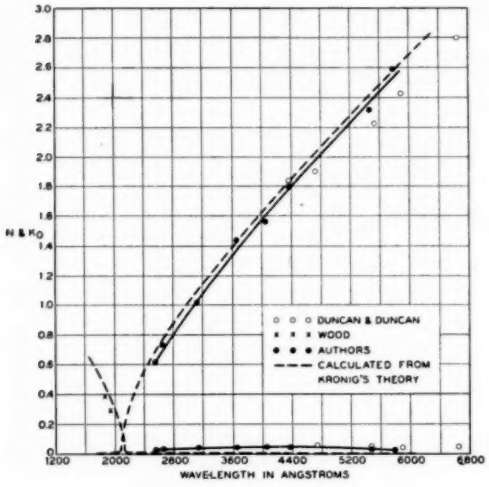


FIG. 2. Dispersion curves of $N$ and $K_0$ for sodium.

addition two comparison plates were measured for each of the five wave-lengths. The total number of spots measured for these five wave-lengths was over 500.

Measurements below λ2536 were not possible due primarily to absorption in the Glan-Thompson prism used in the analyzer position.

## DISCUSSION OF RESULTS

Fig. 2 shows our values of $N$ and $K_0$, together with those of Duncan and Duncan,[5] and two values of $N$ calculated from Wood's[6] reflection measurements. The dotted curve gives the $N$ and $K_0$ calculated after the method of Kronig,[7] using $\sigma_0 = 1.99 \times 10^{17}$ and $\delta = 5.13 \times 10^{12}$. The agreement between the experimental values and those calculated from Kronig's theory is decidedly better than it was for potassium. However, the extremely low values of $N$ predicted by the theory for frequencies below the critical frequency are not realized experimentally.

Fig. 3 shows the reflecting power, for normal incidence, calculated from the formula

$$R = \frac{(N-1)^2 + K_0^2}{(N+1)^2 + K_0^2}.$$

[5] R. W. and R. C. Duncan, Phys. Rev. **1**, 294 (1913).
[6] R. W. Wood, Phys. Rev. **44**, 353 (1933).
[7] R. de L. Kronig, Nature **133**, 211 (1934).

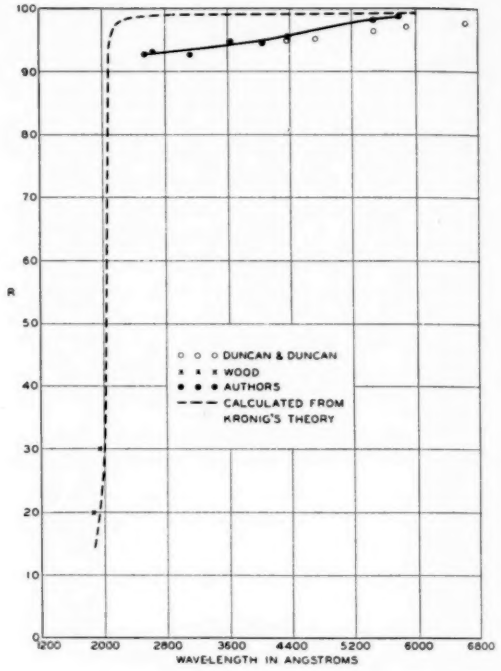


FIG. 3. Reflecting power of sodium.

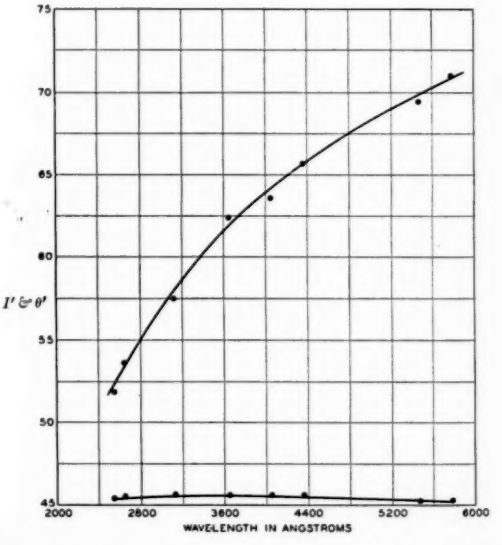


FIG. 4. Principal incidence angle and principal azimuth for sodium.

The values calculated by Duncan and Duncan as well as those obtained by direct measurement by Wood are shown. In addition a curve calculated from the $N$'s and $K_0$'s obtained after the method of Kronig is included. The effect of the small $N$'s of Kronig's theory is to give a very high and almost constant reflecting power below the critical frequency. Experiment indicates a small but definite decrease in reflecting power as the critical frequency is approached from the low frequency side.

The principal incidence angle and principal azimuth, $I'$ and $\theta'$, for sodium are shown in Fig. 4.

# Brightness of Cathodo-Luminescence at Low Current Densities and Low Voltages

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(Received March 8, 1937)

With artificial willemite as the luminescent substance, it is found that, for sufficiently low current densities, $J$, and for accelerating potentials, $V$, between 200 and 800 volts, the brightness of luminescence, $B$, is given quite accurately by $B = KJV^2$. This empirical equation gives too high values if $J$ exceeds a limiting value which depends upon the accelerating potential, and which becomes lower as the potential is raised. From 800 to 1500 volts the agreement is only approximate, $B$ increasing somewhat more rapidly than the equation indicates. There is no indication of the existence of a "threshold" voltage for this material.

The chief difficulty encountered in working at these low accelerating potentials is the uncertainty concerning the potential of the surface of the luminescent target, and one important aspect of the present work is the development of experimental means to determine the potential of this surface to within the limits of experimental error of the other measurements. It is shown that when the target is very carefully shielded electrostatically the secondary emission from it will maintain its potential within a very few volts negative to the potential of the shield, over the entire range of voltages used.

## I. INTRODUCTION

MANY natural minerals, and an even larger number of artificially prepared substances, become luminescent under electron bombardment in a vacuum, the brightness of luminescence depending in some manner upon the concentration of the electrons and upon their speed; and the present investigation of this relationship is an attempt to find conditions which are simple enough and certain enough that the results may lead to a clearer understanding of the primary physical processes involved in this type of luminescence. Interest in these phenomena has been stimulated by the development of the modern cathode-ray tube, but the recent investigations of the brightness of luminescence have for the most part been made in connection with the development of suitable luminescent materials, and have been made at the high current densities and relatively high potentials required by cathode ray tubes. Such conditions are not of the simplest, as is made clearly evident, in the case of the dependence of brightness upon current density, by the data given for commercial cathode-ray tubes and by the published researches made with such tubes as those of Levy and West.[1] For constant accelerating potentials these data show a ratio between brightness and current density which decreases as the current density rises, although Lenard[2] in his pioneer researches in this field found this ratio constant, and most of the earlier workers[3, 4] came to this same conclusion. The principal difference is the current density, which is many times higher in the recent work. Obviously, a first step towards simple conditions is to work with low current densities.

It is not at all so evident that conditions will be simpler at low accelerating potentials, but a more thorough investigation of this range seems very desirable. Although the low brightness obtainable increases the difficulty of making observations at low voltages and low current density, the most serious hindrance to investigations at low voltages has been the uncertainty concerning the exact potential of the luminescent surface, which is always an electrical insulator; and the first step in the present investigation was to develop experimental means for definitely fixing and measuring the potential of this surface.

## II. THE APPARATUS

The cathode-ray beam must produce a uniform electron bombardment over a considerable area of luminescent target; and such a beam, free from lower speed secondary electrons, is not easy to obtain. The arrangement of electrodes finally used is shown in Fig. 1. The negative potential, $V$, accelerates electrons from the oxide-coated platinum filament, $F$, through the openings in the intermediate electrodes to the luminescent

[1] L. Levy and D. W. West, J. I. E. E. **79**, 11–19 (1936).
[2] P. Lenard, Ann. d. Physik **12**, 449–490 (1903).
[3] H. W. Ernst, Ann. d. Physik **82**, 1051–76 (1927).
[4] T. B. Brown, Phys. Rev. **11**, 39–57 (1918).

target, $T$. The boundary of the luminous area is determined by the circular opening, $b$. The current density is controlled by the small positive potential applied to the electrode $G$. The electrode $H$ shields the cathode from the main field, and the opening in it serves as an electron-lens to bring the beam to a focus just below $H$, from whence it diverges quite uniformly for all accelerating potentials above 400 volts. Below 400 volts the distribution is not quite so uniform, the luminescence being noticeably brighter at the center. It is still uniform enough down to 200 volts for the present work although it is hoped possible to improve upon it in the next tube assembly. The main potential source is a 1500-volt full-wave rectifier system, shunted by a potential divider from which any desired voltage may be obtained. During most of the observations here presented the voltages were held steady by means of a simple pentode tube stabilizer circuit.

The luminescent material is placed as a uniform layer of powder in a shallow nickel cup. During the out-gassing operations it was heated to a red heat by high frequency induction, and this sintered it together somewhat. Those luminescent substances which may be used in a vacuum are electrical insulators, and any attempt to make them even partially conducting seriously impairs their luminescent properties.[5] It follows that the current carried to the target by the primary electron beam must be carried away from it by secondary electrons, and may be measured only by collecting these secondary electrons, in this case by means of the screen, $S$, which completely surrounds the target. The anode, $A$, is maintained at a negative potential with respect to $S$ which is sufficiently high to prevent any appreciable number of secondary electrons from reaching it, and this insures the measurement of the entire primary current by the galvanometer, $P$. The anode potential required for this purpose is determined experimentally by use of the auxiliary electrode, $C$, which surrounds the lower end of $A$. This electrode is kept at the same potential as $A$, being connected to it through the galvanometer, $Q$,

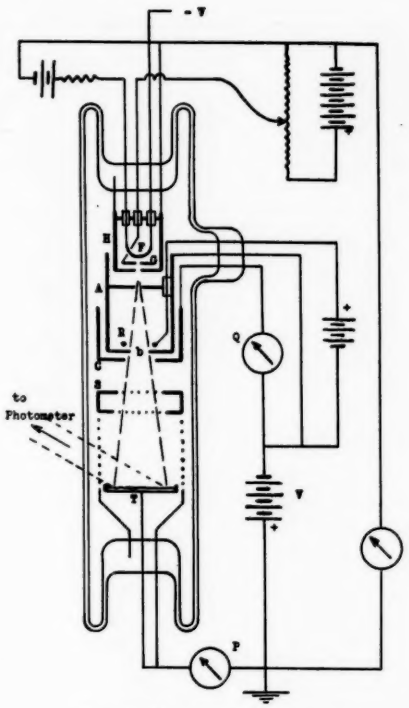


FIG. 1. Diagram of apparatus.

and the potential of $A$ and $C$ together is raised until a negligible current is measured by $Q$. When $S$ screens the target sufficiently well, an anode potential of 22 volts negative to $S$ is sufficient.

Secondary electrons, other than those arising from the luminescent target, may be a troublesome source of error, and must be eliminated from the primary beam and from the current to $S$. The design of the upper electrode system is such as to deflect any secondary electrons out of the primary beam, and those secondary electrons arising from the edge of the diaphragm opening at $b$ are collected by the ring of wire, $R$, placed just above $b$ and held at a small positive potential with respect to $A$.

The striking speed of the electrons is determined by their potential fall from the cathode to the surface of the target. But the insulating nature of this surface raises the question mentioned above—what is the true potential of this surface? Under various conditions it may differ materially from that of the metal cup in which the powder lies, and unless this surface is quite

[5] M. von Ardenne, *The Cathode-Ray Tube* (J. Springer, 1933), p. 88. Pp. 82–88 include much other interesting material concerning screens and screen materials.

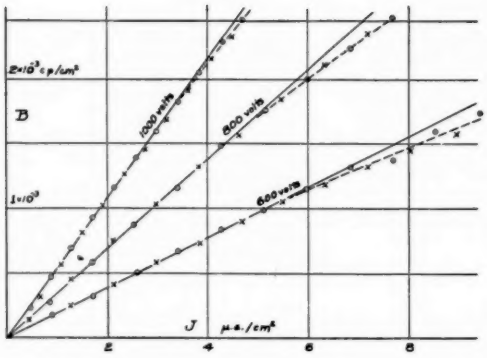


FIG. 2. Constant voltage curves. Brightness of luminescence plotted against current-density: (o) ascending order, (x) descending order.

perfectly shielded electrostatically no reliable answer can be given to this question. With effective shielding the vertical velocity corresponding to the greatest number of secondary electrons (obtained by a method to be described later) was found to be represented by one or two electron volts over the entire range of current densities and of potentials used; and this evidence indicates quite definitely that over this range the potential of the target is essentially that of the shield, *S*, being probably one or two volts negative to it. The shielding here used consists of a double grid of wires above the target, as shown, a grid of wires surrounding it at the sides, and an additional grid at the sides made by painting stripes of colloidal graphite (Aquadag) on the glass walls of the tube, only leaving a window on the side towards the photometer. With less shielding than this, considerably higher negative potentials were required on the anode to prevent secondary electrons from reaching it, showing that the retarding field had built up a negative potential on the surface of the target.

## III. Luminescence Measurements

Once it has been established that the electrical observations are reliable measures of the speed and of the density of the electron stream, the luminescence itself may be investigated. This was done by means of an equal-brightness photometer, the comparison lamp being color-matched to the light from the target. The match was not only good visually, but also quite good spectroscopically, a necessary consideration at these low intensities because of the Purkinje effect. The candlepower of the comparison lamp with the green filter was measured at the National Bureau of Standards with an absolute accuracy estimated at about five percent. The relative accuracy of the photometric measurements is considerably better, the errors being under two percent for all except the lowest intensities.

The candlepower of the luminescent area is measured at an angle of about 60° with the normal and the candlepower per unit area gotten by dividing this value by the projected area of the luminous spot. This is a conventional procedure, assuming Lambert's law to hold. If Lambert's law does not hold (which is quite possible) this procedure is invalid and a systematic error is introduced, which will not, however, affect the *relative* values which are the principal concern of this investigation. In view of this and of other systematic errors in the absolute values of brightness, it is not worth while to correct for losses due to reflection, absorption, etc.

Fig. 2 shows typical constant voltage curves

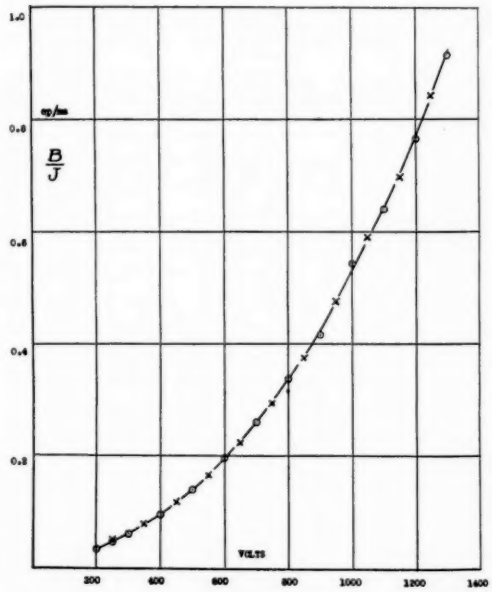


FIG. 3. Brightness per unit current density plotted against accelerating voltage. The brightness for all measurements has been kept within the range for which it is directly proportional to the current density.

for artificial willemite. The lower portion of each curve is straight, as is to be expected when the current density is so low that individual electrons have independent effects. Above this straight portion the line bends towards the $x$-axis. No observable hysteresis or lag was observed, the points taken in ascending order (circles) and those taken in descending order (crosses) following the same line to within the limits of experimental error. This shows best in the curve for 800 volts, which was taken after the voltage stabilizer had been installed. The extent of the straight portion of these curves is greatest at the lowest voltages and diminishes regularly as the voltage is raised.

These results are not in agreement quantitatively with those obtained with commercial cathode-ray tubes. Through the same range of current densities for which these results give straight lines the data obtained with commercial cathode-ray tubes give curved lines which are concave towards the $x$-axis. In part this is due to differences in materials used, and particularly to the use of binders to hold the commercial screens in place. Both Levy and West[1] and von Ardenne[5] discuss the detrimental effects of binders at some length. But in large part this difference is probably due to the method generally employed in making measurements with such tubes. This is the so-called "raster" method, in which an area that appears to be uniformly illuminated is obtained by rapidly deflecting the focused beam in two perpendicular directions across the screen after the manner of "scanning" in television. This gives low average

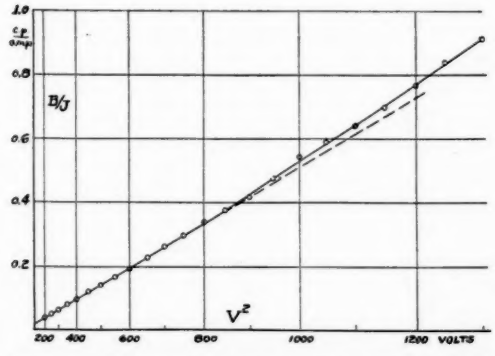


FIG. 4. Brightness per unit current density plotted against the square of the accelerating voltage.

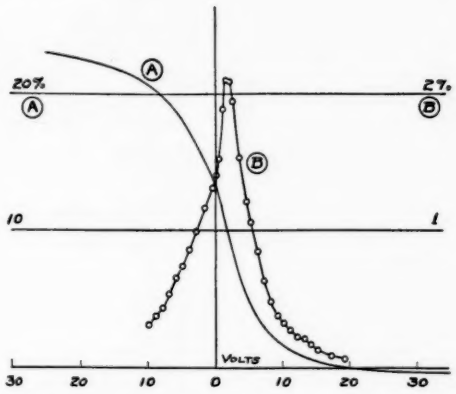


FIG. 5. Secondary emission from the willemite target. (A) Collector current (current to electrode $C$, Fig. 1) plotted against retarding potential ($V_0$). (B) Slope of curve (A), giving the distribution in vertical velocity of the secondary electrons reaching $C$.

current density values, although the instantaneous values at the point of excitation are quite high (or the order of magnitude of $10^{-1}$ amp./cm$^2$). Insofar as the effect of high current density is cumulative over a longer period than the time of passage of the scanning spot over any one point, this procedure is equivalent to a much smaller effective steady current density. But the scanning speed would have to be prohibitively high to make it comparable to a steady current density of the average value.

Next to be considered is the dependence of brightness, $B$, upon the accelerating potential, $V$. So long as care is taken to keep the current density, $J$, within the range for which the ratio, $B/J$, is constant, this relationship may be represented by plotting $B/J$ against $V$, as is done in Fig. 3. This curve resembles in general appearance those obtained by other observers, the effectiveness of the excitation rising rapidly with the voltage. Fig. 4 shows the same data for $B/J$ plotted against $V^2$. Up to about 800 volts this plot is quite accurately a straight line to within the limits of experimental error. It has a small positive intercept on the $B/J$ axis, the cause of which is not clear. It is not due to stray light from outside the tube. It may be due to glow discharge in the tube, although all of the usual procedures of baking, high frequency bombardment, etc. were carried out in the process of evacuation, an efficient getter (Barex) was

used to clean up after sealing off, and the primary beam was invisible at all accelerating voltages. It may be due to light from the filament, although this was entirely too small to be observed separately. It is even possible that it is a real component of the luminescence. Assuming it to be a constant correction factor to the $B/J$ values, the results up to about 800 volts, and for sufficiently low current-densities, are quite accurately represented by $B = KJV^2$. From Fig. 5, $K = 4.94 \times 10^{-4}$, for $B$ in cp/cm², $J$ in amps./cm², and $V$ in volts. Above 900 volts there is a definite departure from this law as the plot shows. It may be significant that this is also in the neighborhood of the soft x-ray excitation limit.

As is indicated by this equation, there is no evidence that the luminescence in this case becomes zero before zero voltage is reached; nor is there any obvious reason to expect the existence of a "threshold voltage" higher than the quantum excitation limit of the fluorescent band, which is too small to show up in these measurements. The only lower limit to the production of luminescence is an electrical one, that set by the ability of the willemite to emit secondary electrons in numbers equal to those in the primary beam. Whenever the secondary emission falls ever so little below the primary current the willemite surface abruptly charges up and thereafter repels all electrons approaching it, even though the voltage be subsequently raised considerably above this limit. This charge leaks off in time, or it may be driven off by the impact of electrons of sufficiently high energy. The potential at which this charging up occurs is sharply defined and remains quite constant in value, at 145 volts under the conditions for which these data were taken. The presence of gas in the tube tends to lower it, and luminescence has been observed (no measurements could be made) down to 40 volts when gas had been admitted to the tube until it was quite "gassy." This phenomenon of surface charging was further investigated after the tube had been opened, the willemite removed, and the tube resealed and re-evacuated. An almost invisible dusting of willemite remained in the cup, sufficient to show whether or not the beam was striking the target, but not enough to have any other effect upon the phenomena observed. With this arrangement, and with the cup insulated from its surroundings, it was found that the behavior of the insulated metal target as regards secondary emission was almost identical to the behavior of the willemite target! Down to 186 volts the secondary emission was adequate to keep the target within a volt or so negative to the potential of the screen, $S$. At 185 volts the nickel cup charged up abruptly so as to repel the electron beam, exactly as was the case with the willemite target. If, however, the external connection to the target is grounded the electron beam again falls upon the target, showing perfectly that the phenomenon is due to electrostatic charging up of the target. Secondary electrons may in this manner charge up glass walls and other insulators within discharge tubes and cause a great many troublesome phenomena. Von Ardenne[5] discusses some of these effects in connection with cathode-ray tubes.

## IV. Secondary Emission Investigations. Determination of the Potential of the Surface of the Luminescent Target

In order to ascertain the potential of the surface of the luminescent target it is necessary to investigate the distribution in velocity of the secondary electrons emitted by it. To do this the retarding potential, $V_a$, applied to the main anode, $A$ (Fig. 1), together with its auxiliary electrode, $C$, was varied, keeping the primary current constant, and the current representing those secondary electrons having sufficient vertical velocities to reach $C$ against this retarding potential is measured by the galvanometer, $Q$. Fig. 5 shows this current (expressed as a fraction of the primary current) plotted against $V_a$. Since the change of this current for any small increment of retarding potential represents the number of electrons having speeds lying in that voltage interval, the slope of this curve, which is also plotted in this figure, gives the distribution in *vertical* velocity of these secondary electrons. In order to obtain accurate slope values the circuit was modified so that the closing of a switch will increase the retarding voltage by just one volt. For parts of the curve which are less

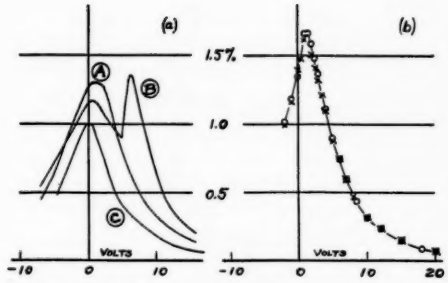


FIG. 6. Secondary emission from the nickel target. (a) Slope curves for several target potentials: (A) zero volts. (B) −6 volts. (C) +22 volts. (b) Slope curve for the "floating" target. (o) Target potential of −1.5 volts, (x) "floating" target, i.e., entirely insulated. This proves that the potential of the "floating" target is −1.5 volts.

steep a two-volt increment is obtained by closing the switch to an alternate position.

Slope curves were worked out in this way for current densities and accelerating potentials representing the entire range of values used in the brightness measurements, and in all cases the potential at which the greatest concentration of electrons occurred was found to be around 1.5 or 2.0 volts, with no significant difference in the curves obtained under different conditions of current and potential.

After the brightness measurements were completed the tube was rebuilt without any luminescent material, as has already been mentioned. Secondary emission data were then taken with the bare metal (nickel) target in the same manner as for the willemite target. In this case however the potential of the target is known and may be maintained at any desired value. Fig. 6(a) shows slope curves for the metal target (A) at zero (screen) potential, (B) at −6 volts, and (C) at +22 volts. Whenever the target is negative by more than a few volts two maxima occur as in the 6-volt case. One of these maxima occurs at zero retarding potential, and the other at a voltage corresponding to the potential difference between the screen and the target. When the target potential is quite close to that of the screen, these two maxima run together, as is shown in Fig. 6(b) for a target potential of −1.5 volts.

In Fig. 6(b) are also plotted slope values for the metal target "floating," i.e., entirely insulated from its surroundings. To within the experimental errors these data fit the same curve as do those data taken for a target potential of −1.5 volts, and this is fairly conclusive evidence that the potential of the floating target is close to −1.5 volts when it is bombarded by 600-volt electrons. If this curve is compared with the slope curve given in Fig. 5 for the willemite target, it is seen that the maximum for the willemite is somewhat higher and occurs at a slightly greater retarding potential. From this it may be assumed that the potential of the willemite target, while slightly more negative than that of the floating metal target, is likewise close to zero, being perhaps two or three volts negative to the potential of the screen.

These results are in fair agreement with those reported in a recent article by Strübig[6]. Strübig finds that the potential of an insulated nickel plate bombarded by electrons remains within ten volts negative of the potential of its surroundings for accelerating potentials between about 100 and 1800 volts, reaching a minimum of around five volts at 450-volts accelerating potential. These values of target potential are slightly larger than the ones here reported, but his method of determining the target potential is a different one, and he was working with much higher current densities ($10^{-4}$ to $10^{-3}$ amp./cm²). His plate did not charge up to cathode potential until about 85 volts was reached. From his observations with the nickel target he concludes that a luminescent target shows a similar behavior. He did not, however, make a detailed study of this case.

It seems safe to conclude that the method here described gives a means for determining with considerable exactness the potential of an insulating surface when it is bombarded by electrons, and that in the case of the willemite target here used its potential was within a very few volts of that of the surrounding screen throughout the range of accelerating voltages and current densities used.

## V. Discussion of Results

The empirical law, $B = 4.94 \times 10^{-4} JV^2$ cp/cm², which seems to fit quite accurately between 200 and 800 volts, is unexpectedly simple. The linear

[6] H. Strübig, Physik. Zeits. **37**, 402–409 (1936).

relation between $B$ and $J$ is to be expected so long as the individual electrons produce independent effects, and the falling off of their effectiveness with higher current densities is a result to be expected when their "ranges" begin to overlap within the average lifetime of an excited "center." But so far no plausible explanation has been found for the proportionality between $B$ and $V^2$. No other workers in this field have mentioned such a law, although the general shape of many of the curves obtained resembles the ones here obtained. The work is to be continued with other luminescent substances to learn whether or not this is a general law.

The significance of this law is made more apparent by expressing it in terms of the number of quanta of visible light which must be excited by each electron for different accelerating potentials. Assuming (1) that Lambert's law holds, (2) that as much radiation takes place into the target as out of it, and (3) that the radiation is all of maximum visibility (the band is narrow, and not far from 5550A), it follows that—

$$\text{Total radiation} = 2\pi B \text{ lamberts/cm}^2$$
$$= 2\pi B/621 \text{ watts/cm}^2$$
$$= 5\times 10^{-6}\, JV^2 \text{ watts/cm}^2.$$

If now the average frequency is assumed to be $5\times 10^{14}$, the average number of quanta of visible light per electron figures out to be $2.5\times 10^{-6}\, V^2$. It amounts to one quantum for ten electrons at 200 volts, and increases to five quanta for one 1400-volt electron.

This is a report of measurements on but one luminescent material, willemite. It is hoped when the methods here described have been applied to the investigation of other materials, both pure and in combination with various binders, etc., that the data obtained may not only be of importance to the practical understanding and use of these materials, but may also provide a basis for better theories for the phenomena involved than those theories which we have at present.

This work was begun at Cruft Laboratory, Harvard University, during the sabbatic year spent there by the author. The many facilities there placed at his disposal and the valuable assistance given him at that time are here gratefully acknowledged. Acknowledgment is also gratefully made to the National Research Council for a grant-in-aid which made the continuation of the work possible, and to the National Bureau of Standards for assistance in the calibration of instruments.

# A High Speed High Precision Microphotometer

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*University of Michigan, Ann Arbor, Michigan*

(Received February 8, 1937)

A microphotometer of new design has been constructed with careful attention to rigidity of mounting and reliability of measurements. The light from a straight filament lamp is condensed on a fore-slit by an $f$ : 1.5 lens without cemented combinations. The fore-slit is imaged on the spectrum plate by a lens combination having an effective aperture of $f$ : 0.75. To avoid further lens losses, a shadow projection on a barrier layer photo-cell is used. The rigidity and precision of adjustment necessary for the use of lenses of such extreme aperture is provided by mounting the optics in an internally threaded brass tube, which is secured to the massive base by a flange, while the spectrum plate is clamped in a suitable frame, mounted on accurate slides. A motor-drive, engaging through a pedal operated clutch, provides a constant speed of traverse, independent of operator technique. A novel method is used for viewing the part of the spectrum under investigation. The wide aperture optical system transmits sufficient light to permit the use of a critically damped galvanometer, with a period of one and one-third seconds. At operating speeds which permit the maximum deflection to be observed accurately, no appreciable galvanometer lag is experienced. Readings of the opacities of five or six preselected lines may be made in one minute, with an error not exceeding one percent. The instrument has the speed and accuracy needed for routine production control work by quantitative spectrographic analysis.

FOR several years, the department of physics has been engaged on various problems in quantitative spectrographic analysis, the work being done chiefly under the auspices of the department of engineering research of the university, which, in collaboration with the various departments of instruction, undertakes research for industrial concerns. All these problems involve the use of a microphotometer to determine the relative intensities of spectral lines of the unknown material and of standardizing lines or marks. When, as is coming to be more and more the case, quantitative spectrographic analysis is used in routine process control, high speed as well as precision is an essential feature of the process and it is necessary to scrutinize each step of the analysis procedure with these ends in view. In this connection, the need has arisen for a microphotometer in which the photographic plate can be mounted easily and quickly, any desired line brought into reading position with a minimum of effort, and a quick single observation of its opacity made without the necessity of taking more than one observation or of making zero or dark current readings; that is, the zero reading must remain constant independent of time, temperature or past history of the indicating system. Since it did not appear possible to find on the market any instrument which met satisfactorily the specifications for the immediate needs, the construction of the apparatus described below was undertaken.

To attain the desired speed of operation, the design has been dominated by the idea that the plate should be in a horizontal and exposed position, both for ease of mounting and for convenience of observation and adjustment. Further requirements were: (1) a motor drive to move any chosen line past the measuring point, (2) arrangement for continuous observation of the region of the plate under investigation by means of a projection system, and (3) sufficient light intensity to enable the use of a galvanometer of a period not greater than two seconds.

The optical system of the microphotometer is shown in Fig. 1. The straight filament argon-filled lamp was built in this laboratory. The filament is of 20 mil tungsten, carries 20 amperes, and is bent in the shape shown to prevent distortion when hot. A Wollensak Velostigmat lens of one-inch focal length and $f$ : 1.5 aperture focuses this filament on a fore-slit, giving an image about one-third the size of the filament. The slit is imaged on the plate by a combination of two two-inch $f$ : 1.5 lenses of the same design, which gives unit magnification on the plate. Practically the full aperture of the lenses is used and suitable diaphragms reduce the intensity of

[1] Department of engineering research.
[2] Department of physics.

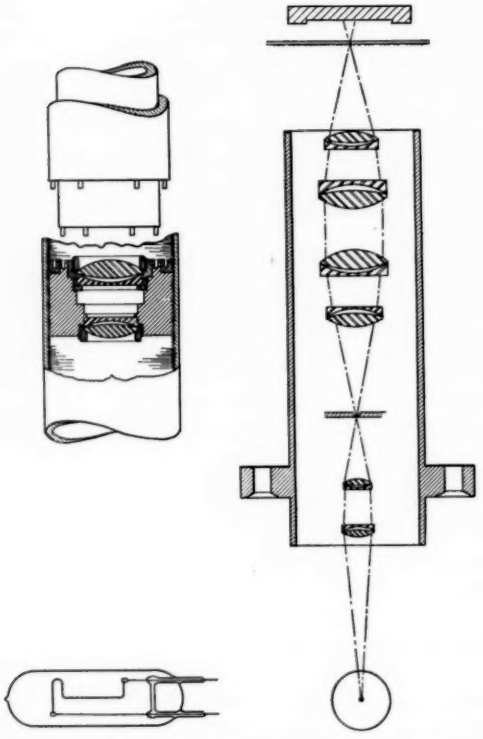

FIG. 1. Details of optical system. The optical system is mounted in a heavy brass tube, threaded inside. The method of adjusting and locking the mountings in position is shown at the left. The lamp, lower left, is a straight filament of tungsten in an argon atmosphere.

scattered light. A slit image of high intensity is produced. To avoid losses of light arising from the use of additional lenses, a shadow projection directly on the photo-cell is used, with a diaphragm on the cell face to cut off all light outside the direct slit beam.

The whole optical system is mounted in a rigid brass tube, which is threaded to receive the lens and slit mountings. A detail of one of the mountings is shown at the side. Two tubes of suitable length, engaging, through pins, the mount and lock-ring, respectively, facilitate precise adjustment of the positions of the lenses and fore-slit. The optics tube carries the lamp housing at its lower end, the whole assembly being supported by a heavy flange which is bolted to the base plate of the microphotometer. The construction is extremely rigid.

Some further details of the optical system are shown in Fig. 2. The optics, as mentioned before, are screwed into a solid tube which carries the light housing at its lower end. This cylindrical brass box can rotate as well as slide up and down on its cylindrical mounting tube and is held by Allen set screws. A removable outer tube, or light shield, permits a ventilating circulation of air but prevents radiation of light into the room. At the bottom of this light housing, the lamp is carried on glass blocks in a leveling mounting, whose details are not shown. Whenever a new lamp is mounted, the filament image must be focused on the slit. To view the adjustment, the ventilator hood is removed, exposing a tubular opening into which is slipped a tube carrying a low power eyepiece and a small mirror. The mirror is of such size and so placed that it intersects part of the rays from every point of the slit and thus permits the complementary part of the rays from the lamp to reach every part of the slit. The slit is thus seen with ample intensity and the filament image readily focused upon it.

In order to permit simultaneous projection both of the slit image and of a part of the plate, a novel feature has been incorporated. This is shown at the right in the illustration. The 50 mm negative lens is coupled to the photovoltaic cell so that either may be swung into the beam. To view the plate, the lens is swung in. A two millimeter axial hole in it permits an image of the slit to be formed on the plate but by only a part of the beam. The rest of the beam is diverged slightly and now comes to a focus in the two-inch $f:3.5$ Tessar lens above. The lower optics thus become a condensing system for this lens, and, after reflection at the right-angle prism and mirror shown, the part of the plate illuminated by the diverged beam is projected on the translucent screen just below the translucent galvanometer scale, and, important for the adjustment, the bright slit image is shown in its proper position in this projection. Thus, by adjustment of the plate carriage, any desired line may be brought up to the slit image, the cell swung in, and a reading taken. It is only an apparent, but not a real, disadvantage that the reading and observation cannot be done simultaneously. It is necessary to read only selected lines, and, as they are brought into position, the

same motion engages the motor drive to take the reading, and shifts the lens and cell.

The cell used is an Electrocell, which has been found to be somewhat more sensitive and to have a smaller dark current than other cells of the blocking-layer type tested. With the lamp and optical system described, the photocurrent for full-light to full-dark is about two microamperes, thus permitting the use of a critically damped galvanometer having a period of one and one-third seconds.

A schematic lay-out of the whole system is shown in Fig. 3. The lamp, slit, and lens system are shown, with the cell in the beam and, at one side, the negative lens coupled to the cell. The plate is clamped in a heavy brass frame, which seems to be the simplest way to hold the emulsion surface of the plate in position as closely as is necessary when lenses of extreme aperture are used.

The cell shown is held in the reading position by the foot treadle, represented at the bottom of the picture. To adjust the plate so that the desired line is brought into position the treadle is released, swinging the cell out and the negative lens in. The plate holder is carried on two sets of mutually perpendicular ways, which, with the aid of the projection system described above, permit a rough adjustment of the plate position. The fine adjustment is made with the hand wheel, which turns a screw carrying a nut attached to the slide system. Thus the desired line is brought up until, on the screen, it is just to the right of the slit image. The treadle is then depressed, throwing in the cell and at the same time engaging, by a clutch, the pulley which is driven continuously by a small electric motor. The motor then draws the line across the slit image on the plate at a rate of twenty-five microns per second. For analysis work, a seventy micron spectrograph slit is used and the microphotometer slit is forty microns. This means that the slit image traverses the line in about two seconds, and the galvanometer, with one and one-third seconds period, easily follows the motion, so that it is necessary to read only the maximum deflection of the galvanometer. The speed is limited by the ability of the observer to follow the motion of the galvanometer beam.

The mechanical details of the instrument are shown in somewhat more detail in Fig. 4. The whole instrument is mounted on a heavy iron bed-plate, 14 by 32 inches, to which the optics tube is bolted. Three steel blocks on the bed-plate

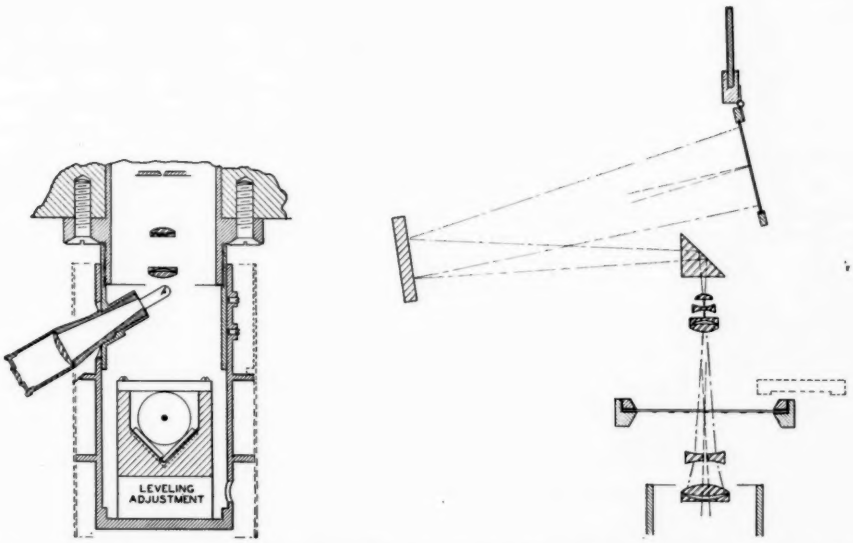


FIG. 2. Further details of optical system. The projection system for viewing the spectrum under investigation is shown in the figure at the right. Details of the lamp housing appear at the left. The removable side tube is for observing the focus of the filament image on the slit.

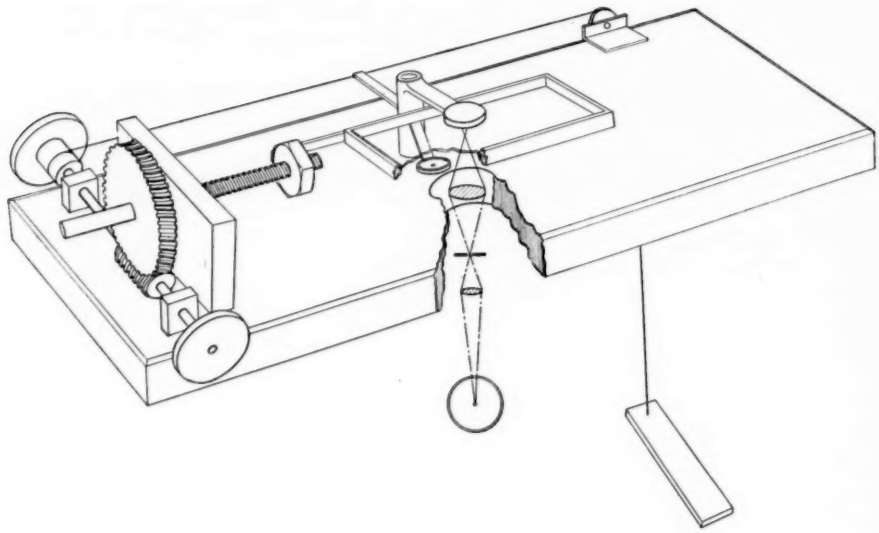

FIG. 3. Schematic diagram of the operating parts of the instrument.

carry two one-inch polished steel rods, on which are six sliding bearings carrying the plate carriage. A cut-out section shows the two sets of slides, at right angles, and a section of the plate-holding frame, with the springs which hold it on the carriage. The whole carriage is drawn by the nut and screw shown. The hand wheel, at the extreme left, permits rapid motion of the screw, while a slow motion, engaging the screw through a clutch, is provided by the worm drive and hand wheel at the front. At the rear of the worm shaft is the clutch which engages the motor driven pulley. The cord which engages this clutch passes, on its way to the treadle, around a pulley, which, as it rotates, turns the cam. The cam, through a roller, moves an arm, which turns the bearing carrying the cell and negative lens arms. This cam is designed to give maximum motion at first and to slow the motion gradually and thus avoid any shock as the motion ends. The restoring motions for clutch and cam are provided by springs.

The microphotometer described is extremely stable and rigid. The rigidity, together with the Julius suspension of the galvanometer, make it practically independent of outside vibration or other disturbances. The Electrocell has very little zero drift, dark current, or temperature effect. The galvanometer zero thus remains steady throughout a set of readings and does not have to be observed for each new reading. The steadiness and constancy make it unnecessary to take more than one reading. The motor drive of the plate makes the reading independent of the operator's technique in moving the line across the slit image and the readings are thus very nearly independent of the operator's skill and experience. Five or six lines previously selected from the same spectrum can be measured in a minute, with an error in such a single reading of less than one percent. This accuracy is sufficient for spectrographic control analysis and the speed is such that the microphotometer operator can read as fast as an assistant can convert the readings graphically into percentage analysis. Thus the new microphotometer satisfies all the requirements of the analytical process for speed, accuracy, and simplicity of operation, and is believed to represent an advance in these particulars.

## ACKNOWLEDGMENTS

The instrument described above was developed and constructed for use in industrial work undertaken by the department of engineering research

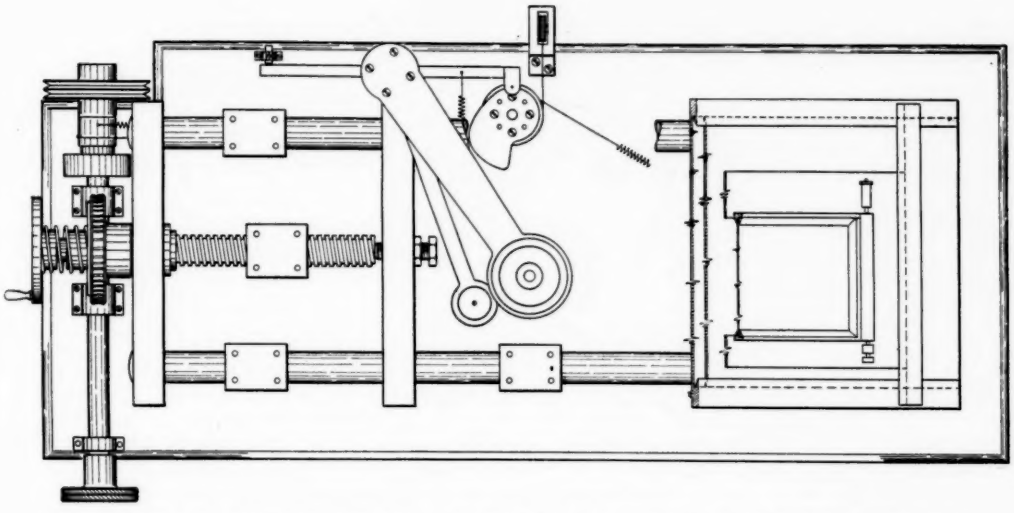

FIG. 4. View of the microphotometer from above with slides cut away to show the operating mechanism.

of the University of Michigan. The apparatus was built in the physics instrument shop by Mr. H. R. Roemer and Mr. W. O. Mintel whose careful work and numerous suggestions contributed materially to the perfection of the instrument.

# Necrology

## William A. E. Drescher

WILLIAM A. E. DRESCHER, vice president of Bausch & Lomb Optical Company, Rochester, New York, died on December 30, 1936, at his home in Rochester, after a brief illness. Mr. Drescher's association with the company had extended over a period of sixty years and he had been active in the administration of the business until two weeks before his death.

Born in Germany, November 8, 1861, he studied at private schools in Berlin before coming to the United States where he completed his studies in the public schools of New York in 1876. His intention had been to follow a profession, but the year he was graduated he was offered a position in the Vulcanite Optical Instrument Company, predecessor of the present company, which was located in New York City. Beginning as an office assistant, he advanced to bookkeeper, handling of credit accounts, salesman in the home office and on the road, and finally into executive work. He served for a number of years as treasurer of Bausch & Lomb before becoming vice president.

He came to Rochester in 1885, when the commercial branch of the Bausch & Lomb Company was transferred to this city.

In 1890 he married Anna Julia Bausch, youngest daughter of John J. Bausch, one of the founders of the Rochester optical company.

An able business executive, Mr. Drescher played an important role in the expansion of the company to its present international prestige. He found time also to serve as director of the Wilmot Castle Company and on the board of directors of the Rochester Savings Bank and the Rochester Trust & Safe Deposit Company.

His professional associations included membership in the Optical Society of America, American Association for the Advancement of Science and the American Microscopical Society, the American Geographical Society in which he was a fellow, the Rochester Historical Society, American Hospital Association, National Tuberculosis Association, American Academy of Political and Social Science, Archaeological Society of America, and the Society of the Genesee. His club memberships included the Genesee Valley Club, Rochester Club and Rochester Country Club.

He is survived by two daughters, Mrs. Joseph F. Taylor and Mrs. Gordon C. Baird; a son, Theodore Bausch Drescher, and eight grandchildren.

## E. O. Dieterich

E. O. DIETERICH, manager of physical research of The B. F. Goodrich Company, died at his home in Akron, Ohio, April 25, 1936. He had been seriously ill with a heart ailment since January. He came to Goodrich and the rubber industry in 1919. Born in Dubuque, Iowa, September 7, 1889, Dr. Dieterich received his A.B., M.S., and Ph.D. degrees from the University of Iowa. He was an instructor of physics at the University of Minnesota (1915–1918) and an assistant professor at the University of Iowa (1918–1919) before he joined the Goodrich organization as a research physicist in 1919. He served in that capacity until 1936, when he was made manager of physical research.

Dr. Dieterich was well known for his contributions to the scientific literature of rubber. He was a leader in the improvement of the plastometer and had written numerous papers on the plasticity of rubber as affected by various steps in the processing operations.

He was a member of the American Physical Society, the Optical Society of America, Sigma Xi Society, a director of the Akron Y. M. C. A., and a member of the Fairlawn Heights Golf Club.

He leaves his widow and a son.